SYNOPSIS

'Development of Impact Resistance Smart Fabric using Shear Thickening Fluid'

Submitted By:

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Introduction:

The rapid advancement of nanoscience and technology is contributing to lot of innovations in many fields including materials science, chemistry, electronics, biology and mechanics. Nanoscience and technology has attracted the attention of researchers from all trades and fields including Physics, Chemistry, Biology and Engineering. The word nano has been taken from a Greek word "dwarf" that means small. Nanoscience refers to the study of structures and materials on nanometer scale. Nanotechnology is the ability of designing, production, characterization and application of these structures by controlling shape and size at nanometer scale.With the help of nanotechnology, a whole new range of machines, fabrics and other objects can be designed by nanomaterials. This technology is advancing with a great pace and has been found to have many applications in energy, medicine, computing, information storage, textiles etc.

A continuous integration of new materials and technology is essential in respect of keen curiosity about improving the ballistic protection, leading to the development of an advanced, smart, flexible and lightweight armor. In the present era of nanotechnology, many researchers are putting their best efforts to merge the nanomaterials and technology in order to provide an improved ballistic protection to the soldiers, police officers and other security personnel. The main function of soft body armor, which is composed of woven ballistic fabrics, is to provide protection to the wearer by resisting the low velocity bullet penetration. However, even if the bullet does not perforate the armor, the wearer can get injured due to the significant deformation of the armor when the bullet is stopped, which is known as blunt trauma. The extent of armor deformation is measured in terms of Back Face Signature (BFS) which must be less than 44 mm according to National Institute of Justice (NIJ) standards [1].

High performance aramid fabrics such as Kevlar and UHMWPE fibres (Ultra high molecular weight polyethylene) such as Dynema are utilized for ballistic protection due to their high strength, low density and high energy absorption. However, around 20-50 layers of such fabrics are required to justify the protection challenge for characteristic ballistic threats, which leads to the reduction in flexibility and increased weight of the armor. Besides this, researches are going on to explore the ballistic performance of various carbon fibres like thornel, celion and ceramic materials like

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Boron, SiC, Alumina and Nextel due to their high modulus and tensile strength. However, in 2003, Lee *et al.* [2] reported that the problem of flexibility and heavy weight can also be overcome by using Kevlar fabric coated with Shear thickening fluid.

In 1971, Poly-paraphenyleneterephthalamide (branded Kevlar), was invented by Polish-American chemist Stephanie Kwolek while working for DuPont. Kevlar is a heat-resistant and strong aromatic polyamide. When Kevlar is spun, the resulting fiber has a tensile strength of about 3,620 MPa i.e. nearly five times that of steel and relative density of 1.44 g/cm3. The polymer owes its high strength to many inter-chain bonds. These intermolecular hydrogen bonds form between the carbonyl and N-H centers. Kevlar maintains its strength and resilience down to cryogenic temperatures (-196 ℃); in fact, it is slightly stronger at low temperatures.

According to NIJ Standard-101.06, [1], soft body armors must meet a number of essential requirements specified by standards. According to these standards, the main function of body armor is to stop the bullet. The second function is to limit the deflection of armor which can cause non-penetrating injuries to internal organs which is known as blunt trauma. The magnitude of blunt trauma is obtained by measuring the depth of indentation in the backing material which supports the body armor during ballistic tests. This indentation is termed as back face signature (BFS) or back face deformation (BFD) which must be less than 44 mm [1]. Besides the magnitude of the indentation, the severity of the injuries to the human body also depends upon the rate of deflection.

Shear thickening fluid (STF) which is also known as dilatant, is a type of non-newtonian fluid i.e. it does not obey the Newton's laws for viscosity. A dilatant or STF consists of a carrier liquid and rigid, colloidal particles suspended in liquid. Silica nanoparticles suspended in polyethylene glycol is an example of such fluid. Various physical and chemical parameters are there on which shear thickening behavior depends such as particle size, particle shape, particle size distribution, particle concentration and particle-particle interactions.

Literature Review:

Over the years, a lot of work has been done for the development of warrior systems that would provide mostly ballistic protection for individual soldier. These systems

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widely known as body armor which are of two types – Soft body armor and hard body armor. The body armor to be used by soldiers must be reliable. So the weight, mobility, and comfort become vital parameters for ensuring their use.

In 1939, Verwey*et al.* [3] reported the shear thickening behavior with the suspension of Iron particles in carbon tetrachloride. To increase the strength, of the mechanism in 1951, Albert, [4] reported that the shear thickening behavior with the suspension of clay-water.

Order-disorder transition mechanism were introduced in 1972, by Hoffman [5], who observed that mono-dispersed suspensions under shear generate diffraction patterns under white light. According to this theory when a shear stress is applied to the suspension, particles align in hexagonally packed layers parallel to plane of shear. But when this shear stress is beyond a critical stress, flow instabilities begin to grow which induce particle motion out of their ordered layers. As a result these particles then collide and jam into each other and hence the viscosity rises.

In 1983, Alliance*et al.* [6] observed the shear thickening mechanism as he used the suspension of calcium carbonate-water. In 1983, Choi *et al.* [7] observed for a wide variety of shear thickening mechanisms as they used polystyrene spheres in silicon oil.In 1989, Bosis*et al.* [8] reported that the rheo-optical measurements confirm the predictions of simulations that shear thickening is driven by dissipative hydrodynamic interactions.

In 1995, Bender *et al.* [9] proposed another mechanism for the explanation of shear thickening is the 'Hydro-cluster' theory. According to this theory, the viscosity of such suspension or STF can be resolved into two components – thermodynamic component and hydrodynamic component where the first one is related to stochastic motion of the particles and second one related with the forces acting between the particles due to the motion through suspension.

In 1995, Boesma*et al.* [10] reported different kinds of rheometers such as rotational rheometer and capillary rheometery used for the investigation of rheological mechanism of shear thickening fluids.

In 1998, Dischler*et al.* [11] reported that dry powders exhibiting dilatant property were used to increase volume and viscosity under ballistic impact or similar kinds. They used Kevlar fibers coated with a dry powder that exhibits dilatant properties.

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Dilatant properties refer to increases in both volume and viscosity under flow. In their work, the fibers demonstrated an improved ability to distribute energy during ballistic impact due to the enhanced inter-fiber friction.

In 2001, Cannon, [12] reported that the usual method to reduce blunt trauma is to add more number of layers of aramid fabric but it is done at the expense of increasing weight and reducing flexibility of the armor. In 2003, Lee *et al.* [13] studied the ballistic impact characteristics of STF impregnated Kevlar fabrics. They observed improvement in ballistic performance of Kevlar fabrics impregnated with STF.

In 2003, Daniel *et al.* [14] purposed a dimethyl-siloxane-hydro-terminated polymer, such as Dow Corning 3179 material, being a dilatant compound or a lightweight version, incorporating Duolite spheres or a derivative. The dilatants material remained soft and flexible until it was subjected to the impact when its characteristics changed rendering it temporarily rigid. The carrier could be coated or impregnated with the dilatant compound in various ways.

In 2003, Lee *et al.* [2] conducted a study to improve the ballistic property of Kevlar woven fabric by applying STF to the fabric. The STF treated Kevlar was expected to remain flexible at normal conditions and instantly harden upon impact.

In 2004, Wagner *et al.* [15] reported that many carrier fluids have been used, including water, ethylene glycol (EG) and polyethylene glycol (PEG). However, EG or PEG is the most widely used carrier fluid in STF due to its high stability, high boiling point and non-flammable properties. A typical STF was made of silica nanoparticles suspended in polyethylene glycol.

In 2004, Wetzel *et al.* [16] performed experiments to study the effect of rheological parameters on the STF. They observed that concentrated suspensions with various particle concentration show shear thinning at low shear rates followed by shear thickening at high shear rates. The shear thickening response increases as particle concentration increases whereas the critical shear rate decreases as the particle concentration increases.

In 2005, Sauer *et al.* [17] impregnated a low glass transition, viscous polymer fluid, as a liquid adhesive additive, acted as a friction modifier, into a fibre structure such as a polyaramid fabrics.

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In 2005, Tan *et al.* [18] reported that this blunt trauma, however, can also be reduced by impregnating ballistic fabric with shear thickening fluid.

In 2006, Wagner *et al.* [19] studied the rheology of a colloidal PEG-based shear thickening fluid emulsified with silicone oil and found that a shear thickening response was observed in the viscosity-shear rate curves for volume fraction as low as 10% of STF in the silicone emulsion.

In 2006, Fischer *et al.* [20] purposed that the colloidal dispersions have attracted the attention of scientists and they are under investigation since many decades due to their interesting flow behaviors, which make them applicable in various industrial sectors such as ceramics, foodstuffs, paints, mineral slurries, pulp and paper, coatings, reinforced plastics and filled elastomers.

Also, increasing need of nano-technological inventions and nano-composites result in the generation of new areas for use of colloidal suspensions.'Colloid' usually denotes the dispersed phase of a two-component system in which the elements of the dispersed phase are too small to be easily observed by an optical microscope and whose motion is affected by thermal forces. When the suspending medium is liquid, they do not readily sediment. Colloidal solutions are prepared by dispersion of nanoparticles into a medium fluid, consolidation, removal of the liquid phase, and densification.

In 2007, Kalman*et al.* [21] also observed the results for the mono-dispersed PMMA-PEG suspension at various concentration levels. With the increase in particle concentration, the maximum viscosity of the STF increased while the critical shear rate decreased

In 2008, Cohen D [22] stated that the STF has held promises in many industrial applications. Some patents protected certain applications while others invented certain shear thickening fluids with potentials of various applications. He described a shear thickening fluid used in conjunction with fabrics utilized in an expandable spacecraft.

In 2008, U.S. Department of Justice [1] reported the Ballistic resistance of body armor *NIJ standard- 101.06*.

For many decades, man has used various types of soft body armor such as animal skin, silk and nylon, etc. to protect himself from injury in combat. But in 2009, David *et al.* [23] usually made soft body armor of high strength materials such as Kevlar,

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Twaron, Dacron and Spectra which have excellent ballistic resistant properties. Soft body armor consists of various layers of fabrics. When a bullet strikes the fabric, it gets caught in a web of yarns to which its kinetic energy is transferred. As a result, two waves propagate from the point of impact i.e. in-plane wave and transverse wave.

In 2009, Wagner *et al.* [24] reported that in equilibrium, random collisions among the particles make them naturally resistant to flow. At first particles get organized in the flow, as the shear stress increases, due to which the viscosity decreases. With further increase in shear stress hydrodynamic interactions dominates the stochastic one leading to the formation of hydroclusters. These hydroclusters produces higher rate of energy dissipation and a sudden increase in viscosity.

In 2009, Sauer *et al.* [25] found the viscous polymers effective in many different types of fibrous structures with a result of an optimal ballistic resistance and protection against blunt trauma in body armor.

In 2010, Sochi [26] stated the characteristic features of fluid as compared to a solid that can be deformed easily. Even though a fluid can deform easily, but its viscosity induces resistance to its flow. Fluids can be of two types simple and structured. In general, when a fluid system has a uniform phase, such as a solution or pure substance, it is termed as a simple fluid and those which contain more than one phase like solid particles dispersed in a liquid or an emulsion of immiscible liquids are considered as structured fluids. On the basis of rheological behavior fluids can be of two types, Newtonian fluid and Non-Newtonian fluid.

In 2010, Brown *et al.* [27] found that shear thickening can be controlled via changing surface properties of particles (e.g. hydrophilic or hydrophobic), roughness, shapes and measuring conditions.

In 2011, Cavallaro [28] reported that the future improvements of such fabrics will be increasingly difficult to achieve because the financial values associated with developing new fibers are becoming cost-prohibitive.

In 2013, Ding *et al.* [29] reported that the shear thickening fluids show unique rheological behavior as at low shear rate it behaves like a normal liquid. But when the shear rate exceeds a certain value the viscosity rises abruptly and STF behaves like a solid. As the shear stress gets removed it again begins to act like a normal liquid. Mostly, shear thickening outcome from a stable suspension becoming flocculated due

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to stress experienced under shear. For this to happen there must be no net attractive forces b/w the particles in beginning. Particles can be stabilized by electrostatic forces, solvation forces, or steric forces. Concentrated suspensions of non-aggregating particles mostly demonstrate reversible shear thickening. The certain value of shear rate above which a sudden transition occurs in STF from liquid to solid phase is termed as critical shear rate. This critical shear rate varies significantly among various systems. The maximum value up to which viscosity of the STF rises in shear thickening region also varies significantly between the different systems.

In 2015, Das *et al.* [30] reported that the kinetic energy dissipates through yarn deformations and inter-yarn friction when they slide against each other. Soft aramid fabric layers with considerable thickness allow a projectile to be stopped over a longer distance. Inter-yarn friction improves the ballistic performance until a critical value beyond which increase in friction may affect the dissipation of energy.

In 2017, Asija*et al.* [31]prepared shear thickening fluid samples using solvent separation technique for which they processed water dispersed colloidal silica Since in this method one dispersion medium is completely exchanged with another so it is also called Solvent exchange technique.

In 2019, Majumdar*et al.* [32] used soft body armor panels using p-aramid (Technora) fabrics with three different levels of thread densities were developed. Ballistic evaluation of plain woven aramid fabrics with three different thread densities have been carried out. The impact energy absorption increased with the increase in thread density in STF treated Kevlar fabric.

Research Gap identification:

The application of shear thickening fluid on Kevlar fabrics improves the impact energy absorption by the soft composite as the viscosity of the former increases dramatically during impact. Shear thickening fluid, based on nanoparticles dispersed in a carrier phase has the potential to play a significant role in the research of more efficient body armors. Such dispersions behaves like a fluid but on facing a shear stress its viscosity raises abruptly due to which it begins to behave like a solid. This unique property of STF can be used for manufacturing a light weight and more flexible armor. A part of the study will be devoted to society, concentrated on weight reduction of the composite panel.

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Proposed Objectives: This present work is undertaken with following objectives:

1. To investigate topographical, morphological and thermal characteristics of silica nanoparticles.
2. To synthesize and characterize the shear thickening fluid.
3. To study the tuning of rheological behavior of STF by addition of different additives.
4. To enhance the performance of Kevlar fabric.
5. To study the effect of rheological properties on ballistic performance.

Proposed Methodology:

1. The topographical, morphological and thermal characteristics of silica nanoparticles will be studied by using Scanning Electron Microscope (SEM), Dynamic Light Scattering (DLS) and Thermo-Gravimetric Analysis (TGA), respectively.
2. Synthesis of shear thickening fluid using SiO_2 will be done by sonication, homogenization method and sonication method followed by homogenization. Rheology will be used as a characterization tool to investigate the shear thickening behavior of the prepared STF samples at room temperature. Rheology will be done in two modes: Steady state and Dynamic state. Steady shear measurements will be conducted to observe the change in viscosity and stress values of STF with increasing shear rate. While in the dynamic tests both the strain sweep at constant frequency and the frequency sweep at constant strain will be done to understand the viscoelastic response of the shear thickening fluids.
3. Various physical and chemical parameters on which shear thickening behavior depends such as particle morphology, particle size distribution, particle concentration and particle-particle interactions will be thoroughly studied. The effect of various hydrophobic/ hydrophilic spherical, cylindrical shaped additives such as grapheme oxide, surface hydroxyl rich cellulose beads and Kevlar fabric will be thoroughly investigated to study the rheological behavior of silica based STF.
4. STF will be coated on Kevlar fabric by dip coating technique. In order to measure the residue velocity after impact, UHMWPE and STF treated Kevlar based composite panels will be fabricated using different layers of these materials.

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5. Energy absorption by the soft armor panel will be measured by measuring the difference in impact and residue velocity of the panel. The extent of armor deformation will be measured in terms of back face signature (BFS), which will depend upon the ammunition to be chosen, distance range, temperature, area of impact.

Thesis Outline: Thesis will comprise five chapters as:

Chapter 1: Introduction – includes brief about shear thickening fluids,alsocalled Dialatent,shows a increase in viscosity with increase in shear stress. Its coating on high performance aramid fabric Kevlar has shown a good response in ballistics.

Chapter 2: Literature Review – since 1939 as started by Verwey et.al. shear thickening behavior is being studied. Over the years it has been seen STF treated Kevlar show increased impact energy absorption with increase in thread density of STF.

Chapter 3: Methodology – synthesis of shear thickening fluid of colloidal silica nanoparticles,by sonication method followed homogenization. Rheology will be used as characterization tool next. STF will be coated on Kevlar by dip coating technique.Energy absorption by soft body armor will be measured by measuring the difference in impact and residue velocity of the panel.

Chapter 4: Results and Discussion – The results are then to be elaborated and will be discussed for future scope.

Chapter 5: Conclusions – finally conclusion is drawn.

Chapter 6: References – All the references will be written as per ACS Guidelines.

Research Plan Schedule: The research plan schedule of proposed research titled "Development of New Shear Thickening Fluid Impregnated Kevlar Fabric Composite Panels for Improved Impact Resistance" is as under:

Year 1: In the first year following work will be done:

- Review of literature
- Characterization of silica nanoparticles
- Synthesis of STF
- Tuning the rheological behavior of STF

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- Coating of STF on Soft Armor Panel

Year 2: In the second year following work will be done:

- Enhance the surface properties of nanoparticles
- Method development for rheological characterization
- Effect of additives on rheological behavior of STF
- Effect of mass fraction of additive on steady state and dynamic rheology
- Energy absorption of the Soft Armor Panel

Year 3: In the third year following work will be done:

- Method development for the coating of STF on Kevlar fabric
- Effect of particle size or concentration on coating
- Development of composite panel of STF coated Kevlar fabric
- Energy absorption study of developed composite panel
- Weight reduction of the soft armor panel

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